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Search for CP violation using T-odd observables in charm meson decays

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Summary. — A search for CP violation using T-odd observables is performed using singly Cabibbo-suppressed $D^0 \to K^+K^-\pi^+\pi^-$ decays at LHCb. This method has a different sensitivity to the CP violation, and is an almost systematic uncertainty free approach. Searches for CP violation in different phase space regions and as a function of the D^0 decay time are also performed.

1. – Motivation

The CP violation (CPV) in charm decays is predicted to be very small in the Standard Model (SM) [1, 2], however, recent calculations do not exclude effects up to a few times 10^{-3} [3-5]. A significant excess of CP violation with respect to the SM prediction would be a signal of new physics. Further more, the study of CPV in singly Cabibbo-suppressed decays is particularly sensitive to the effect of new physics [2]. The analysis of four-body charm decays probes for CPV in different phase space regions, and the sensitivity can be enhanced due to several interfering amplitudes with different relative strong phases.

2. – Experimental technique

In four-body $D \to p_1p_2p_3p_4$ decays, using triple products of final state particle momenta in the D centre-of-mass frame, $C_T \equiv \vec{p}_3 \cdot (\vec{p}_1 \times \vec{p}_2)$ for D and $\overline{C_T} \equiv \vec{p}_{\bar{3}} \cdot (\vec{p}_{\bar{1}} \times \vec{p}_{\bar{2}})$ for $\overline{D}$ decays, two T-odd observables,

$$(1) \qquad A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}, \qquad \overline{A_T} = \frac{\Gamma(-\overline{C_T} > 0) - \Gamma(-\overline{C_T} < 0)}{\Gamma(-\overline{C_T} > 0) + \Gamma(-\overline{C_T} < 0)}$$

can be studied [6], where $\Gamma_D(\Gamma_{\overline{D}})$ is the partial decay width of $D(\overline{D})$ decays to $p_1p_2p_3p_4(p_{\bar{1}}p_{\bar{2}}p_{\bar{3}}p_{\bar{4}})$ in the indicated $C_T(\overline{C_T})$ range. However, an asymmetry A_T can arise from final state interactions (FSI) even without CPV [6,7]. To cancel FSI contamination, a well defined CP-violating observable is

$$a_{CP}^{T-odd} \equiv \frac{1}{2}(A_T - \overline{A_T}). \tag{2}$$

By construction, a_{CP}^{T-odd} is insensitive to the production asymmetry of D and charged track reconstruction asymmetry. Therefore, the systematic uncertainties in this technique are usually very small.

Further more, a_{CP}^{T-odd} is proportional to $\sin\phi\cos\delta$, where ϕ is the relative weak phase and δ is the relative strong phase between two interfering partial waves [8, 9]. In a $D^0 \to V_1V_2$ decay (where V_i is a vector meson), a_{CP}^{T-odd} is sensitive to CPV in interference between even and odd partial waves of the V_1V_2 system [8].

3. – Previous measurements

There are several previous measurements of a_{CP}^{T-odd} in charm decays: FOCUS measured $a_{CP}^{T-odd}(D^0 \to K^+K^-\pi^+\pi^-) = (1.0 \pm 5.7 \pm 3.7)\%$, $a_{CP}^{T-odd}(D^+ \to K_s^0K^+\pi^-\pi^+) = (2.3 \pm 6.2 \pm 2.2)\%$, and $a_{CP}^{T-odd}(D_s^+ \to K_s^0K^+\pi^-\pi^+) = (-3.6 \pm 6.7 \pm 2.3)\%$ [10], and BaBar measured $a_{CP}^{T-odd}(D^0 \to K^+K^-\pi^+\pi^-) = (0.10 \pm 0.51 \pm 0.44)\%$ [11], $a_{CP}^{T-odd}(D^+ \to K_s^0K^+\pi^-\pi^+) = (-1.20 \pm 1.00 \pm 0.46)\%$, and $a_{CP}^{T-odd}(D_s^+ \to K_s^0K^+\pi^-\pi^+) = (-1.36 \pm 0.77 \pm 0.34)\%$ [12]. All results are consistent with no CPV.

4. – Measurements at LHCb

Using $3\,\mathrm{fb}^{-1}$ data sample recorded at LHCb detector in 2011 and 2012, about 1.7×10^5 $D^0 \to K^+K^-\pi^+\pi^-$ decays are reconstructed from $B \to D^0\mu X$ decays (where X indicates any system composed of charged and neutral particles) [13]. The flavour of D^0 meson is identified by the charge of the muon. The triple product is defined as $C_T \equiv \vec{p}_{K^+} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$. The selected data sample is split into four subsamples according to the flavour of the D^0 and the sign of $C_T(\overline{C_T})$, as shown in fig. 1. The asymmetry parameters A_T and $\overline{A_T}$ are extracted directly from the simultaneous fit to these four subsamples. The fit model is made of two Gaussian distributions for signal and the exponential shape for background. The asymmetries A_T and $\overline{A_T}$ are included in the fit model as

$$\begin{aligned} N_{D^0,C_T>0} &= \frac{1}{2}N_{D^0}(1 + A_T), \\ N_{D^0,C_T<0} &= \frac{1}{2}N_{D^0}(1 - A_T), \\ N_{\overline{D^0},-\overline{C_T}>0} &= \frac{1}{2}N_{\overline{D^0}}(1 + \overline{A_T}), \\ N_{\overline{D^0},-\overline{C_T}<0} &= \frac{1}{2}N_{\overline{D^0}}(1 - \overline{A_T}). \end{aligned} \tag{3}$$

Three approaches to search for CPV are performed: the phase space integrated measurement, measurements in different phase space regions, and measurements as a function of the D^0 decay time. The phase space is divided into 32 regions using a binning scheme based on the Cabibbo-Maksimowicz parametrisation, while 4 regions are used in the D^0

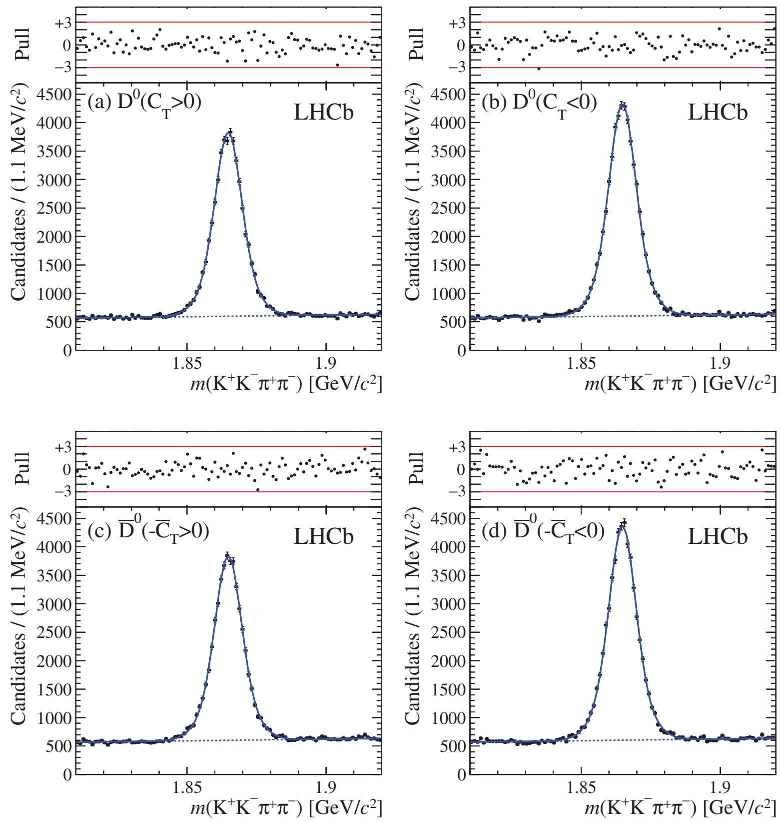

Fig. 1. – Distributions of the $K^+K^-\pi^+\pi^-$ invariant mass in the four samples defined by $D^0(\overline{D^0})$ flavour and the sign of $C_T(\overline{C_T})$. The results of the fit are overlaid as a solid line, and a dashed line is used for representing the background. The normalised residuals (pulls) of the difference between the fit results and the data points, divided by their uncertainties, are shown on top of each distribution.

decay time, requiring similar signal events in each region. The results of the integrated measurement are

$$\begin{aligned} A_T &= (-7.18 \pm 0.41(\text{stat}) \pm 0.13(\text{syst}))\%, \\ \overline{A_T} &= (-7.55 \pm 0.41(\text{stat}) \pm 0.12(\text{syst}))\%, \\ a_{CP}^{T-odd} &= (0.18 \pm 0.29(\text{stat}) \pm 0.04(\text{syst}))\%, \end{aligned} \tag{4}$$

The relatively large asymmetries observed in A_T and $\overline{A_T}$ are due to FSI effects [6, 7], which are difficult to predict [14]. a_{CP}^{T-odd} is consistent with no CPV hypothesis.

For the measurements in the different phase space regions, the asymmetry is calculated in each region, and a χ^2 test with respect to CP conservation hypothesis is performed. The result is compatible with no CPV with a p-value of 74%, based on $\chi^2/\text{ndof} = 26.4/32$, as shown in fig. 2. The asymmetries A_T and $\overline{A_T}$ are significantly different among the different regions, which can be explained by the rich resonant structure of the hadronic four-body decay that produces different FSI effects over the phase space [15].

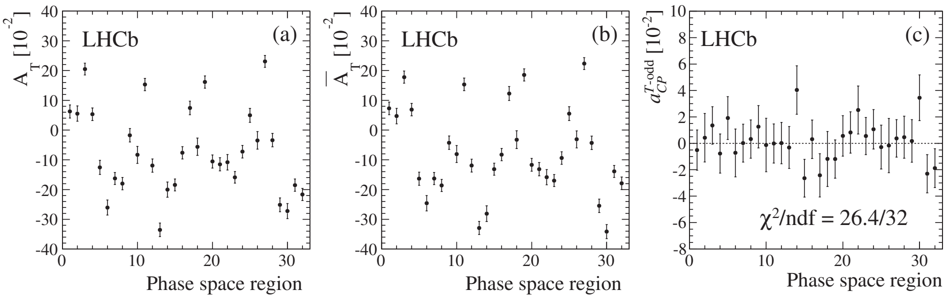

Fig. 2. – Distributions of the asymmetry parameters (a) A_T, (b) $\overline{A_T}$ and (c) a_{CP}^{T-odd} in 32 regions of the phase space.

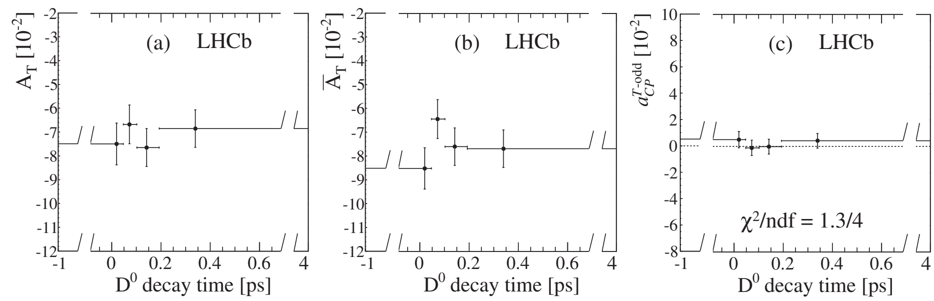

Fig. 3. – Distributions of the asymmetry parameters (a) A_T, (b) $\overline{A_T}$ and (c) a_{CP}^{T-odd} as a function of the D^0 decay time. For a_{CP}^{T-odd}, the value of the χ^2/ndof for the CP conservation hypothesis, represented by a dashed line, is also quoted. The scale is broken for the first and last bin.

For the measurements in the D^0 decay time, the asymmetries are shown in fig 3. The result is consistent with no CPV hypothesis with a p-value of 86%, based on $\chi^2/\text{ndof} = 1.3/4$. The A_T and $\overline{A_T}$ do not show any significant dependence as a function of the decay time, and the results are compatible with constant functions.

5. – Summary

Using T-odd variables is a complementary approach to search for CPV. LHCb collaboration exploited this technique to search for CPV in $D^0 \to K^+K^-\pi^+\pi^-$ decays. Three methods are performed: measurement integrated over the phase space, in different phase space regions and as a function of the D^0 decay time. All results are consistent with no CPV.

This technique is an alternative approach for precision CPV searches at LHCb with very small systematic uncertainties, and also very promising for LHCb upgrade.

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